MANUFACTURE, ASSEMBLY, AND DELIVERY
OF BERYLLIUM TEST PANELS

Lockheed Missiles & Space Company, Inc.
A Subsidiary of Lockheed Aircraft Corporation
Space Systems Division
Sunnyvale, California

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Prepared for

NASA-GEORGE C. MARSHALL SPACE FLIGHT CENTER
Marshall Space Flight Center, Alabama 35812
FOREWORD

This is the Final Report prepared by Lockheed Missiles and Space Company (LMSC) for NASA Contract NAS8-27074, "Manufacture, Assembly, and Delivery of Beryllium Test Panels." Documented in this report are the LMSC efforts performed for the National Aeronautics and Space Administration, George C. Marshall Space Flight Center, Marshall Space Flight Center, Alabama 35812, under the direction of the Science and Engineering Directorate, Research and Process Technology Division, Metals Joining Development Branch, Metal Processing Section. Mr. Charles N. Irvine, S&E-PT-MWP was the Contracting Officer's Representative (COR) for this program.

Program responsibility at LMSC was assigned to the Space Systems Division, Manned Space Programs, Thermal Protection Systems Group. Mr. A. Bruce Burns was the LMSC Project Leader. Technical support was provided by the following individuals: Mr. D. L. Owen, Mr. E. W. Bauer, Mr. F. L. Conover and Mr. John Rasmussen (Manufacturing); Mr. D. L. Moss (Brazing); and Mr. R. E. Lord (Quality Assurance).
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INTRODUCTION AND SUMMARY

This report documents and summarizes the processing techniques utilized by LMSC to fabricate two beryllium heat shield panels for NASA/MSFC. Each panel is 0.99 meter (39 in.) square, with a transverse slip joint located at the center of the panel. The two halves of each panel are joined by flexible clips at the center slip joint; continuous standoffs are provided at either end. The panel skins contain formed circular arcs on 7.62 cm (3 in.) centers that are oriented perpendicular to the center transverse slip joint; 2.54 cm (1 in.) flats are provided between arcs, to which hat-section panel stiffeners are attached by brazing. The clips and standoffs that nest inside the panel stiffeners are attached to the panel with screws and nut anchors.

Engineering requirements for the panels were established by NASA/MSFC and are contained in the following drawings:

- NASA/MSFC Dwg J31M01040, Sheets 1 and 2, Rev. A, dated March 1, 1971, Test Panel Assembly, Beryllium
- NASA/MSFC Dwg D31M01041, Rev. A, dated March 1, 1971, TPS Panel, Test, Beryllium
- NASA/MSFC Dwg D31M01042, Rev. A, dated March 1, 1971, Standoff-Panel, Test, Beryllium
- NASA/MSFC Dwg J31M01045, Rev. A, dated March 1, 1971, TPS Panel Assembly, Test
- NASA/MSFC Dwg D31M01046, Rev. A, dated March 1, 1971, Panel Stiffener, Beryllium
- NASA/MSFC Dwg C31M01271, dated August 6, 1970, Nut Anchor (Configuration Only; Material for Nut and Basket, Stainless Steel, A286 per AMS 5735)
Certain details in the drawings were subsequently modified as discussed later in this report. Because these drawings utilize the customary U.S. System of Units, this system was used during the program to make measurements and calculations. However, the International System of Units is the principal system employed in this report, as required by the terms of the contract. Customary units are given in parentheses for the benefit of the reader.

Activities for the program were divided into two phases: Phase I involved steps leading up to and including fabrication of detail parts, and Phase II consisted of assembly of parts and delivery of the finished panels to NASA/MSFC. This report has been organized in accordance with this phasing. Furnace brazing studies conducted in preparation for the Phase II effort are also included with the Phase I documentation.
All of the steps leading up to and including fabrication of detail parts were accomplished during Phase I. These steps were as follows:

- Establish material requirements, order material, and verify mechanical properties upon receipt
- Design, fabricate, and check out tooling to form detail parts and to braze subassemblies
- Generate processing techniques for both forming and brazing, as required
- Fabricate detail parts

1.1 MATERIAL REQUIREMENTS AND INSPECTION

Previous LMSC experience in forming beryllium parts was used to determine beryllium cross-rolled sheet requirements at the beginning of the program. The average attrition rate employed was approximately 50 percent. Layouts of blanks in the sheets were based on a procedure in which a greater-than-average attrition was allocated to the largest blanks on the assumption that the largest parts would be hardest to form. If after forming the required parts some blanks remained, these blanks could then be divided into blanks for smaller detail parts. Likewise, remnants of cracked blanks could conceivably be used to fabricate smaller parts. This procedure resulted in more kerf, but provided maximum backup material for all parts.

Material was ordered to Specification MIL-B-8964, with the exception that elongation required by par. 3.3 was 10 percent minimum in 2.54 cm (1 in.). Minimum tensile properties required by this specification are:

- Ultimate tensile strength = $4.827 \times 10^8$ N/m$^2$ (70 ksi)
- Tensile yield strength (0.2 percent elongation) = $3.448 \times 10^8$ N/m$^2$ (50 ksi)
A nominal gage of 0.091 cm (0.036 in.) was selected for ordering. This gage represents the thickness of the clips and standoffs plus allowances for sheet tolerance and etching of parts after forming and drilling. Although the 0.051 cm (0.020 in.) thickness of the panel skins and stiffeners is considerably less, this same starting gage was also selected for these parts in order that material for attrition could be transferred for the fabrication of any part as discussed above. While the trend in the cost of the material per unit of surface area is generally down as the sheet gage is reduced (but not below 0.066 cm (0.026 in.), this trend is partially offset by price adjustments which depend upon the total quantity of material ordered in any given nominal gage and the sizes of the sheets to be ordered.

A firm material order was placed with Kawecki-Berylco Industries, Inc. (KBI) on April 20, 1971. The material was received in two shipments on August 25 and August 30, 1971. Mechanical properties furnished with the sheets by the producer were as follows:

<table>
<thead>
<tr>
<th>Sheet No.</th>
<th>Direction</th>
<th>UTS (10^8 N/m^2)</th>
<th>(ksi)</th>
<th>0.2%YS (10^8 N/m^2)</th>
<th>(ksi)</th>
<th>% El.</th>
</tr>
</thead>
<tbody>
<tr>
<td>HR-1440</td>
<td>L</td>
<td>5.19</td>
<td>(75.2)</td>
<td>3.86</td>
<td>(56.0)</td>
<td>17.0</td>
</tr>
<tr>
<td></td>
<td>T</td>
<td>4.94</td>
<td>(71.7)</td>
<td>3.81</td>
<td>(55.3)</td>
<td>23.0</td>
</tr>
<tr>
<td>HR-1439</td>
<td>L</td>
<td>5.12</td>
<td>(74.3)</td>
<td>3.91</td>
<td>(56.7)</td>
<td>13.0</td>
</tr>
<tr>
<td></td>
<td>T</td>
<td>4.94</td>
<td>(71.6)</td>
<td>3.93</td>
<td>(57.0)</td>
<td>13.0</td>
</tr>
<tr>
<td>HR-1441</td>
<td>L</td>
<td>5.00</td>
<td>(72.5)</td>
<td>3.88</td>
<td>(56.3)</td>
<td>13.0</td>
</tr>
<tr>
<td></td>
<td>T</td>
<td>4.92</td>
<td>(71.4)</td>
<td>3.85</td>
<td>(55.8)</td>
<td>15.0</td>
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</table>

Subsequently, LMSC performed in-house tests on each sheet and recorded the following results:

<table>
<thead>
<tr>
<th>Sheet No.</th>
<th>Direction</th>
<th>UTS (10^8 N/m^2)</th>
<th>(ksi)</th>
<th>0.2%YS (10^8 N/m^2)</th>
<th>(ksi)</th>
<th>% El.</th>
</tr>
</thead>
<tbody>
<tr>
<td>HR-1440</td>
<td>L</td>
<td>(No test, sample cracked)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>T</td>
<td>4.87</td>
<td>(70.6)</td>
<td>3.81</td>
<td>(55.3)</td>
<td>14.0</td>
</tr>
<tr>
<td>HR-1439</td>
<td>L</td>
<td>4.97</td>
<td>(72.1)</td>
<td>3.63</td>
<td>(52.6)</td>
<td>12.0</td>
</tr>
<tr>
<td></td>
<td>T</td>
<td>4.92</td>
<td>(71.4)</td>
<td>3.74</td>
<td>(54.3)</td>
<td>12.0</td>
</tr>
<tr>
<td>HR-1441</td>
<td>L*</td>
<td>4.71</td>
<td>(68.3)</td>
<td>3.83</td>
<td>(55.5)</td>
<td>7.0</td>
</tr>
<tr>
<td></td>
<td>T*</td>
<td>5.01</td>
<td>(72.7)</td>
<td>3.94</td>
<td>(57.2)</td>
<td>7.0</td>
</tr>
</tbody>
</table>

*Broke outside test section
It may be observed that the LMSC test results for the first two sheets meet specification requirements and compare favorably with the producer's data. However, the LMSC test results for the third sheet show percent elongations that are considerably below the producer's data and also below specification requirements. In addition, the ultimate tensile strength obtained by LMSC in the longitudinal direction of this sheet is less than the minimum required by specification. These low results were attributed to the fact that both specimens from the third sheet broke outside the test section near the radius leading to the grip area and, thus, the accuracy of the data, in particular the percent elongation, is somewhat in doubt. Although replacement specimens would have been desirable, it was not possible to positively identify additional material as having been cut from the third sheet. The timing of the arrival of the material with respect to the scheduled test panel delivery necessitated the immediate cutting of the sheets into blanks before the test results were obtained. In view of this, the third sheet was accepted on the basis of the producer's data and the agreement between LMSC's data and the producer's data for the remaining sheets, which retests on the third sheet would be expected to duplicate.

The producer provided a topographical thickness map with each sheet, as shown in Figs. 1 through 3. These maps show thickness variations that are well within the specification limits of ±0.0127 cm (±0.005 in.); in addition, a tendency toward crowning in the sheets may also be observed.

Subsequent forming of this material into detail parts resulted in attrition rates for certain parts which substantially exceeded the planned rate. In particular, relatively high attrition rates were experienced for the D31M01041A panel skin and the D31M01042A standoff. Additional material was ordered from KBI on December 9, 1971 and delivered in two lots on January 3 and January 24, 1972. This order consisted of four pieces 102 cm by 53 cm (40 in. by 21 in.) which were nominally 0.079 cm (0.031 in.) thick. Mechanical properties furnished by the producer with these pieces are shown below; topographical thickness maps provided by the producer are reproduced as Figs. 4a through 4d. An additional piece of nominally 0.130 cm (0.051 in.) thick material measuring 81 cm by 112 cm (32 in. by 44 in.) was also purchased (Sheet No. HR-1544). Mechanical properties and a topographical thickness map provided by the producer (KBI) for this sheet are also shown below and in Fig. 4e, respectively. These additional material requirements resulted in an actual average attrition rate which was double the planned rate.
Fig. 1 Topographical Thickness Map for Sheet HR-1440

NOTE: FIRST VALUES ARE IN CENTIMETERS; VALUES IN PARENTHESES ARE IN INCHES.
<p>| | | | | | | | | | |</p>
<table>
<thead>
<tr>
<th></th>
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<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>0.089</td>
<td>0.0876</td>
<td>0.091</td>
<td>0.089</td>
<td>0.091</td>
<td>0.091</td>
<td>0.089</td>
<td>0.0927</td>
<td>0.086</td>
<td></td>
</tr>
<tr>
<td>(0.035 )</td>
<td>(0.0345)</td>
<td>(0.036 )</td>
<td>(0.035 )</td>
<td>(0.036 )</td>
<td>(0.036 )</td>
<td>(0.035 )</td>
<td>(0.0365)</td>
<td>(0.034 )</td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.0953</td>
<td>0.097</td>
<td>0.099</td>
<td>0.099</td>
<td>0.102</td>
<td>0.099</td>
<td>0.099</td>
<td>0.0997</td>
<td>0.0927</td>
</tr>
<tr>
<td>(0.0375)</td>
<td>(0.038 )</td>
<td>(0.039 )</td>
<td>(0.039 )</td>
<td>(0.040 )</td>
<td>(0.039 )</td>
<td>(0.039 )</td>
<td>(0.039 )</td>
<td>(0.0365)</td>
<td>(0.034 )</td>
</tr>
<tr>
<td></td>
<td>0.0953</td>
<td>0.097</td>
<td>0.099</td>
<td>0.099</td>
<td>0.099</td>
<td>0.099</td>
<td>0.099</td>
<td>0.102</td>
<td>0.091</td>
</tr>
<tr>
<td>(0.0375)</td>
<td>(0.038 )</td>
<td>(0.039 )</td>
<td>(0.039 )</td>
<td>(0.039 )</td>
<td>(0.039 )</td>
<td>(0.039 )</td>
<td>(0.040 )</td>
<td>(0.036 )</td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.089</td>
<td>0.089</td>
<td>0.091</td>
<td>0.089</td>
<td>0.0902</td>
<td>0.091</td>
<td>0.089</td>
<td>0.0927</td>
<td>0.086</td>
</tr>
<tr>
<td>(0.035 )</td>
<td>(0.035 )</td>
<td>(0.036 )</td>
<td>(0.035 )</td>
<td>(0.0355)</td>
<td>(0.036 )</td>
<td>(0.035 )</td>
<td>(0.0365)</td>
<td>(0.034 )</td>
<td></td>
</tr>
</tbody>
</table>

Note: First values are in centimeters; values in parentheses are in inches.

Fig. 2 Topographical Thickness Map for Sheet HR-1439
Fig. 4 Topographical Thickness Maps for Sheets:

(a) H-1545-1, (b) H-1545-2, (c) H-1546, (d) H-1463, and
(e) HR-1544

1-7
It may be seen that all of this material meets the specification requirements for strength and elongation which were established for this program.

1.2 TOOLING

Tools were required for this program to form the detail parts and to fixture the subassemblies for furnace brazing. Because both the forming and brazing operations are performed at temperatures above $978^\circ K (1300^\circ F)$, tools were fabricated principally from high-alloy steels with coefficients of thermal expansion that closely matched the coefficient of thermal expansion of beryllium at the forming temperature. Also, these alloys were selected to minimize spalling and the deposition of constituents on the beryllium. All tools were inspected for compliance with engineering requirements after fabrication. All tools were classified as fabrication aids because of the developmental nature of the program and the small production run of parts. Fabrication aids are not formally controlled and are generally scrapped upon completion of the work.

The tool for forming the D31M01043A-1 and -2 exterior clips and the C31M01044A interior clips is shown in Fig. 5. Fabricated from 17-7PH steel, the tool is equipped with locating pins at the crest of the male half. These pins, which correspond to the fastener pattern in the finished part, are used to locate the blank in the die and to assure that an 0.051 cm (0.020 in.) offset between the flanges of the clip, as required by the drawing, is correctly oriented with respect to the clip fastener pattern. Holes are provided in the tool to adjust the position of the pins for forming either internal or external clips. The tool is also used to locate holes for fasteners in the flanges of the clip and to provide a backup surface for the parts during drilling. The tool was designed for furnace heating.
Fig. 5 Tool for Forming Exterior and Interior Clips, With Formed Exterior Clip
In contrast, the tool for forming the D31M01042A standoff, shown in Figs. 6a through 6c, is a heated tool designed for bench operation because of the multiple forming operations required for the part. This tool, also fabricated from 17-7PH steel, is composed of several parts that properly position and index the blank in the tool and form the various bends in the part. The figures show the three principal forming positions: Fig. 6a illustrates the position for forming the top of a mid-span bend, Fig. 6b illustrates the position for forming the side of a mid-span bend, and Fig. 6c shows the position for forming an end return flange. This tool successfully forms the D31M01042A standoffs; however, a final stress relief and sizing is required to ensure flatness and uniformity in the part. The fixture for performing this operation is shown in Fig. 7. Actual operation of these tools is discussed in Section 1.4.

Tooling for the D31M01046A stiffeners is shown in Fig. 8. The tool, fabricated from 17-7PH steel, is designed to form these parts in one operation, using a blank trimmed to the developed-width but having greater than required length so that it can be positioned over locating pins as shown in the figure. The tool was designed for furnace heating, and the first run off production parts used this method of heating the tool. However, a second run of replacement parts was produced by heating the tool with calrods which were mounted in a hydraulic press as shown in Fig. 9.

The D31M01041A panel skins were formed in the tool shown in Fig. 10. The bottom or male portion of this integrally-heated ceramic die was cast from Pyro-Form* to a machined aluminum pattern. The mating surface of the die, although originally cast to the bottom half of the die, was ground smooth when the definition of the cast arcs was judged unacceptable; high alloy steel bars accurately located in the flats of the panel skin provide the forming action when the two halves of the die are brought together. This tool was designed and fabricated after the initial tooling proved to be unsatisfactory. A review of the forming trials performed with both tools is presented in Section 1.3.

*A commercial product made under license to the Lockheed-California Co.
Fig. 6a. Tool for Forming Standoffs, Showing Position for Forming Top of Mid-Span Bends
Fig. 6b Tool for Forming Standoffs, Showing Position for Forming Side of Mid-Span Bends
Fig. 6c Tool for Forming Standoffs, Showing Position for Forming Ends
Preparations for furnace brazing of the J31M01045A panel assemblies consisted of positioning and supporting the parts with the fixtures shown in Fig. 11 and, subsequently, sealing the assembled panel with fixtures in the retort shown in Fig. 12. The fixtures were designed to have a minimum amount of mass (which absorbs and holds heat during the braze cycle) and yet provide sufficient pressure to ensure contact between mating parts both during handling of the retort and at the brazing temperature. This objective was achieved by placing the parts to be brazed between two U-shaped stiffeners that were fastened together with A-286 CRES Steel bolts at either end outside of the panel assembly. The U-stiffeners contained a small built-in convex bow that ensured contact of mating parts in the middle of the panel. Rene' 41 spring clips were placed underneath the bolt heads to compensate for thermal growth at the brazing temperature of the bolts holding the U-stiffeners together. The U-stiffeners themselves were fabricated initially from 17-7PH steel that was heat-treated to the TH1100 condition, in order to closely match the coefficient of expansion for beryllium. Locating holes were provided in the bottom of each U-stiffener at either end to align with holes in the parts for attachments. The 17-7PH U-stiffeners were subsequently replaced with Hastelloy X U-stiffeners after the first J31M01045A panel assembly had been furnace brazed.

The brazing retort, shown in Fig. 12, was fabricated from stainless steel. Relatively large flanges were provided so that the retort could be reused a number of times after the weldments sealing the retort for each braze cycle were milled off. Inlet/outlet tubes to the retort were also stainless steel; thermocouple leads were brought out through the discharge tube.

Brazing fixtures also were required to position beryllium pads for brazing to the interior and exterior clips and standoffs. (Nut anchors were subsequently riveted to these pads; see Section 1.3.) Examples of the fixturing employed for the standoffs are shown in Fig. 13. Rene' 41 wire pins were inserted in the rivet holes, and a Rene' 41 spring clip spanning the pins provided pressure between the mating parts. Similar fixturing was used for brazing the pads to the clips.
Fig. 13 Fixtures for Brazing Beryllium Pads
1.3 VERIFICATION OF PROCESSING TECHNIQUES

Prior to manufacturing the actual panels, a number of forming and brazing trials were accomplished to ensure that adequate processing techniques were available. The forming trials dealt principally with proving out the acceptability of the tools; the brazing trials involved verification of the brazing process.

1.3.1 Forming

Tool-try parts were drawn from all forming tools described in Section 1.2. The tool-try parts representing the D31M01042A standoffs and the D31M01041A panel skins were formed on subsize blanks, owing to the fact that this work was performed prior to the receipt of material for this program. Parts were formed successfully on all tools. Subsequently, it was found that whereas there were no unforeseen problems involved in moving from the subsize blank to the full-size blank for the D31M01042A standoffs, there were difficulties in moving up to the full-size blanks for the D31M01041A panel skins.

The tooling originally designed to form the panel skins is shown in Fig. 14, and the subsize tool-try part formed with this tool is shown in Fig. 15. The part is seen to be the full 50.8 cm (20 in.) length but width was limited to 30.5 cm (12 in.) in place of the full-size 99 cm (39 in.) width. This part was formed by heating the tool with inserted blank by direct contact with an integrally heated ceramic block and creep-forming in a hydraulic press using insulation blankets to contain the heat of the die. Indexing the part over the die, which would be necessary for the production parts, could not be demonstrated due to the small size of the blank. However, this was not expected to be a problem. A new press-mounted furnace designed for use in a larger press was scheduled to be operational for the forming of production parts. The design of this furnace permitted heating of the tool and blank in the press and indexing of the blank through small access doors to reduce heat loss. Subsequent trial runs with the press-mounted furnace resulted in insufficient form in the full size parts. This was attributed to the use of thick steel plates attached to the upper and lower platens of the press (to reduce the shut height to an opening consistent with the height of the tool) which were not parallel within required limits. In addition, these preliminary trials brought out some deficiencies in the furnace that effectively eliminated it from further use on this program.
Fig. 15 Subsize Panel Skin Formed on Discarded Tool; Bruzed Stiffener Shown in Upper Portion
These problems were related to the equipment and not to the tooling. Therefore, the tool was removed to the press which had been used previously to form the subsize part shown in Fig. 15. The first attempt, using insulation blankets to maintain the required forming temperature, produced the subsize part shown in Fig. 16. This part was formed by using the female base plate of the tool and rubber forming the arcs into the part one at a time. It may be seen that very good definition of the arcs in the panel skin was obtained (compare Figs. 15 and 16). This definition was accomplished by placing bars over the finished arcs and locking them into position to prevent the rubber from drawing material out of the formed arc as the neighboring arc was formed. When this technique was scaled up to the full-size blank, severe warpage of the blank was encountered, as shown in Fig. 17, due to the large thermal gradients over the length of the part.

After several attempts to correct this problem, it was concluded that the warpage could not be relieved in this set-up and that a full-size, heated die (shown previously in Fig. 10) was required. This die provided more uniform heating and cooling of the part, and controlled the majority of the warpage.

A production part formed with this tool is shown in Fig. 18. Although a high-alloy steel die with a coefficient of thermal expansion closely matching that for beryllium at forming temperature would have been preferred, the die was cast from the ceramic material Pyro-Form in order to meet scheduling and budgeting requirements for this program. Similar ceramic dies have been in use at LMSC for some years to form Agena skin panels. The primary consideration in specifying this die material centers on properly accounting for its low coefficient of thermal expansion, both in designing the die and in cooling down the part after forming.

1.3.2 Brazing

Trials were conducted to verify the processes for brazing beryllium to beryllium, and beryllium to A286 steel nut anchors. The braze alloy used in these trials was BAg 18 as specified on the drawings. This alloy, which has a nominal composition of 63 Ag–27 Cu–10Sn, was used in foil strip form, 0.0076 cm (0.003 in.) thick. The principal objective of the trials was to identify the process that results in good wetting of the
Fig. 16 Subsize Panel Skin Formed by Rubber Forming on Female Portion of Discarded Tool
Fig. 18 Panel Skin Formed on Final Tooling
parts to be brazed, but at the same time minimizes the brittle beryllium-copper intermetallic zone that forms as a function of the maximum brazing temperature and time at maximum brazing temperature.

The result of the first beryllium-to-beryllium braze trial was shown previously in Fig. 15. This figure shows a full-size D31M01046A stiffener brazed to a portion of a D31M01041A panel skin. The braze cycle was performed after the parts were fixtured as shown in Fig. 11 and the assembly was placed inside the stainless steel retort (Fig. 12). The retort was loaded into a cold box furnace. Stainless steel tubing was attached for argon supply and discharge, and the retort was purged overnight with dry (206°K (-90°F) dewpoint) argon. Thermocouple leads were brought out through the discharge tube.

The brazing cycle was accomplished in the following steps: (1) heating to 922°K (1200°F) and holding until uniformity within 6°K (10°F) was indicated between the furnace and retort thermocouples, (2) rapidly heating to 1033°K (1400°F) in approximately 10 minutes, (3) holding for 10 minutes in the range 1033–1039°K (1400–1410°F), and (4) cooling by furnace shutoff and opening the door. Gas flow during the cycle was monitored by bubbling the discharge argon through oil. A retort pressure of 5 cm (2 in.) of water was maintained during the cycle.

The brazed joint was inspected radiographically and ultrasonically, with results indicating a 90 percent or better braze. Small voids (0.16 cm, 1/16 in.) or less in diameter were randomly scattered in the braze. An area of larger voids about 3.8 cm (1-1/2 in.) long occurred about 15.24 cm (6 in.) from one end.

Subsequent microanalysis showed that wetting of both beryllium surfaces had occurred in the void area, which led to the conclusion that the voids had been caused by local relaxation of the fixturing during the early portion of the cooling cycle before the braze had solidified. It was determined that this relaxation was caused by the retort having been placed on the furnace hearth, with the fixturing in direct contact with the retort. Upon cooling, the hearth was relatively slow to cool, causing a non-uniform temperature condition in the fixturing. The solution to this problem was to use an alternate...
furnace with a roller hearth. In a similar way, the problem could have been solved by placing the braze assembly on a rack within the retort. For the production braze assemblies, both the rack and the roller hearth were used.

The quality of the brazed joint is illustrated in Fig. 19. This figure shows two magnifications of a section of the joint cut transverse to the stiffener about 10 cm (4 in.) from one end. A 500x magnification of the section is shown in Fig. 19a and a 1000x magnification is shown in Fig. 19b. Phases are identified: the silver-copper-tin eutectic in the center of the braze zone, a layer of beta-beta prime (beryllium/copper), and a thin layer of Be₃Cu at the braze interface.

Microhardness indentations shown in the photomicrographs indicate relative hardness (Vickers DPH) of the various constituents. Diffusion of copper into the beryllium is shown by the hardness of the basic beryllium at DPH 214 varying to DPH 94 near the interface. The hardness value of the Be₃Cu is not accurate, because the indentation is wider than the phase being tested. However, the diagonal measurement along the intermetallic indicates a hardness not less than DPH 226. The hardness of the silver-copper-tin braze eutectic varies from DPH 89 to DPH 273.

Although the layer of beryllium/copper intermetallic at or near the braze surface was considered to be sufficiently thin in this specimen, other cycles with lower braze temperatures were also investigated. Small braze specimens, which were cycled in a vacuum furnace using a partial pressure of approximately 1 torr of argon, showed wetting of the braze to the beryllium at 1011ºK (1360ºF) with considerably less intermetallic diffusion than that shown in Fig. 19. Photomicrographs of one of these specimens is shown in Fig. 20. Diffusion of copper into the beryllium could not be detected by microhardness, and no softening was indicated, even at the braze interface. The Be₃Cu intermetallic is significantly thinner to the extent that microhardness indentations could not be made in this constituent, although the effects of the hard layer are shown on the indentations adjacent to the interface. Other than as noted, hardness readings are identical to those quoted for Fig. 19. Bleeding of polishing fluids was noted at the interface, indicating porosity inasmuch as no evidence of cracking was found. The porosity is believed to be the result of marginal wetting of the beryllium by the braze, due to the low temperature of the braze cycle.
Fig. 19a Photomicrograph of 1033°K (1400°F) Braze Structure – 500x Magnification
Subsequently, a second trial to braze a full-size D31M01046A stiffener to a portion of a D31M01041A panel skin was performed with the fixtures and retort described previously. Braze coverage of this joint was reduced (due to over-pressurization of the retort), resulting in distortion of the retort and the sample. However, braze wetting and quality were acceptable. The braze cycle consisted of: (1) heating to 811°K (1000°F) to obtain temperature uniformity, (2) rapidly heating to 1011°K (1360°F), (3) cooling by shutting-off the furnace and allowing part and furnace to cool to 922°K (1200°F), and (4) opening the door of the furnace to permit cooling at a more rapid rate. Radiographic examination of the braze joint revealed an area approximately 20 cm (8 in.) long by 1.3 cm (0.5 in.) wide containing large voids caused by the joint being disturbed when the buckling occurred.

As a result of these trials, a braze cycle based on a maximum temperature of 1022°K (1380°F) was adopted for the production assemblies. This temperature represented a compromise between the superior wetting observed in the 1033°K (1400°F) tests and the smaller intermetallic diffusion zone determined in the 1011°K (1360°F) tests.

The drawings call for brazing A-286 steel nut anchors to the beryllium clips and standoffs so that screws attaching these parts to the panel skins may be installed blind from the top of the panel. Preliminary trial attempts to braze these joints were aimed at obtaining a satisfactory braze without resorting to the use of the retort. The principal driver in these studies was cost; if such a process could be used, the cost of fixturing the nut anchors, sealing and handling the retort, and utilizing the box furnace could be eliminated. These same arguments apply also to the use of a vacuum furnace in the event one were used in place of a retort.

The techniques investigated included torch braze, spotwelding with braze alloy interlayer, and gas tungsten arc spotwelding with braze alloy interlayer. Some samples prepared with these processes, as well as by furnace brazing, are shown in Fig. 21. In general, it was found that while some of the specimens gave the appearance of sound braze joints, the joints were poor metallurgically. In particular, the spotwelded
Fig. 21 Sample Beryllium-to-A286 Steel Nut Anchor Braze Specimens From Several Processes: Spotwelded and TIG Braze Welded Specimens (Left) and Furnace Brazed Specimens (Right)
joints* showed evidence of excessive temperature and explosion of the braze alloy from the joint. These problems may be partially attributed to the lack of sufficient specimens within the scope of this contract to fully optimize the required machine setting for the processes. As a result of this limited investigation, it was concluded that techniques for brazing the nut anchors to beryllium outside of the retort were not adequately developed at this time for production usage.

Several A-286 nut anchors were subsequently furnace brazed to beryllium. These brazes were generally unsuccessful for one or more of the following reasons: (1) braze alloy failed to wet the A-286 nut anchor; (2) braze alloy failed to wet the beryllium; (3) delamination of the braze/beryllium interface subsequent to brazing. One of the specimens with delamination is shown in Fig. 22. One possible explanation for this lack of success is the difference in the thermal coefficients of expansion for the two materials at braze temperatures. In addition, although the nut anchor surface was cleaned prior to assembly by grinding and wire-brushing, the resulting surface may not have been free of the effects of passivation to which the nut anchors were subjected by the vendor.

A review of the results of these attempts to braze A-286 nut anchors to beryllium pointed out that although the results were generally unsatisfactory, failures of some of the better specimens had occurred in the form of delamination in the beryllium adjacent to the joint when thrust loads were applied to the screws during installation and removal. It was concluded, therefore, that even if the nut anchors were satisfactorily and consistently brazed to the beryllium, failures could occur during assembly or disassembly, presumably because of the low short transverse elongation usually found in beryllium sheet. This conclusion ultimately resulted in a contract change notice to rivet the nut anchors to the beryllium in lieu of brazing. This change included a requirement for brazing small beryllium pads to the beryllium parts (between the nut anchor and the part) to eliminate a knife-edge condition in the beryllium parts caused by machine-countersinking 0.283 cm (3/32 in.) diameter monel rivets into nominally 0.076 cm (0.030 in.) sheet. The details of the drawing revisions for this change are presented in Appendix A.

*See NASA/MSFC Metallurgical Laboratory Work Request Completion Report MW-85-71, dated July 7, 1971
1.4 FABRICATION OF DETAIL PARTS

Blanks for the majority of the parts were cut from the sheets by using a high-speed, lubricated, abrasive cutting wheel mounted in an enclosure subjected to negative pressure. The blanks for the interior and exterior clips, being nonrectangular in shape, were prepared by other means. The number of interior clips required made the preparation of an Electrical Discharge Machining (EDM) electrode economical, and these blanks were cut by this process. The blanks for the exterior clips were machined. The clip and stiffener blanks were subsequently drilled and etched for locating pins. With the exception of the stiffener length dimension, the clip and stiffener blanks were cut to the developed dimensions of the part, thereby eliminating
the need for trimming. Some example blanks are shown in Fig. 23. During forming of the parts, all tools were coated with a graphite lubricant to promote draw of the beryllium at the forming temperature.

The D31M01043A-1 and -2 exterior clips and the D31M01044A interior clips were formed on the tool shown previously in Fig. 5 by heating the tool and blank in an oven, removing them when they had reached 1033°K (1400°F), and forming the blank into the tool in a small hydraulic press. The part was left in the die to cool and thus minimize warpage. As noted in Section 1.2, the fastener holes in the crest of the clips were drilled in the blank and were used for locating the blank in the tool. Holes for the fasteners in the flanges were drilled after forming. Figure 5 shows a D31M01043A exterior clip after forming and etching were completed.

The D31M01042A standoffs were formed on the tool shown in Figs 6a through 6c. Mid-span forms were produced initially; the ends were trimmed and formed last. Figure 6a shows the tool setup for forming the top of a mid-span form. The section of the tool at the top (with handle) rotates to force the metal to the shape of the tool. During actual forming, insulation slabs are mounted about the tool to maintain a forming temperature of approximately 1000°K (1350°F). With the top formed, an additional section of the tool is added to form the side of each mid-span form, as shown in Fig. 6b. The part is then removed from the tool, inverted, and reinserted into the tool in the position shown in Fig. 6a. The above process is then repeated until all mid-span forms have been completed. The final process is the forming of the end bends, which is done by wrapping the hot material around the tool by hand as shown in Fig. 6c. Because the part is nonuniformly heated during the forming process and is constantly being removed from the die and inverted, dimensional control is not within acceptable tolerance when the final bend is made. Stress relieving and hot sizing are required, using the tool shown in Fig. 7. Both heavy bars shown in the figure have locating pads corresponding to the proper location of the flat areas at top and bottom of the standoff. The part is loaded in and the pads attached in place; the assembly is then placed in a furnace, heated to approximately 1000°K (1350°F), and allowed to cool slowly. A D31M01042A standoff, after removal from the fixture and cleaning, is shown in Fig. 24. This figure also shows a standoff that was lost during subsequent
Fig. 24 Standoff After Stress Relief and Hot Sizing (Left); Standoff With Failure Due to Drilling (Right)
drilling for the nut anchors. The drilling operation, followed by etching, completed the detail work on this part. Because of the numerous operations involved in fabricating this part, the attrition rate was relatively high. A total of thirteen blanks were required to obtain four production parts.

The D31M01046A panel stiffeners were formed on the tool shown previously in Fig. 8. These stiffeners were formed from blanks cut to the developed width size as shown in Fig. 23. The forming process for the first production run paralleled that used for forming the exterior and interior clips; i.e., the tool and blank were heated in an oven to approximately 1033 K (1400°F), then they were removed and placed in a small hydraulic press to be creep-formed into the tool. All forming was performed in one operation, and the part was left in the die to cool in order to minimize warpage. Following cleaning, the ends of the stiffener were trimmed and holes were drilled as required. Etching completed the detail processing of the part. As previously noted, a second production run of D31M01046A panel stiffeners was produced for replacement parts. The fabrication procedure for these stiffeners varied somewhat from the first production run in that calrods were mounted in the hydraulic press, as shown in Fig. 9, and used as a source of heat for the tool and blank.

In all of the forming of detail parts discussed this far, parts were lost due to cracking. Several broken stiffeners are shown in Fig. 25 along with one production part. The broken parts are typical in that failure generally occurred at the ends of the blank near the locating hole. This may be due to several factors. The forming of multiple bends at one time requires some stretching of the beryllium, and the success of this process is highly dependent upon the absence of stress risers at the hole and at the edge of the blank. Successful forming must also be performed at the proper temperature and, in some cases, the temperature of the ends of the blank may have dropped below the forming temperature. Finally, it appeared in some attempts that the blank hung to the tool. This may have been caused by a lack of adequate lubrication, or by the fact that the blanks varied in gage as noted in Figs. 1 through 4. Blanks on the high side of the permissible tolerance may not have had sufficient clearance in the tool. It is assumed here that the base material had uniform properties throughout the sheet. This was probably not the case because, the cutting the blanks, the blade appeared to occasionally encounter areas which were obviously harder than adjoining areas. A
Fig. 25 Finished Stiffener (Left) With Several Failed Parts: Stiffener at Left Was Trimmed at End and Drilled for Attachment After Forming
variation in formability in these areas can be expected. Of the several possible causes of lost parts noted above, forming temperature and die clearance are probably most important. A considerably lower loss rate was experienced in the second production run of D31M01046A stiffeners where the die was maintained continuously at forming temperature. In addition, the hot die was cleaned with steel wool between parts for this production run, and as a result no blanks were lost due to gross fracture.

The D31M01041A panel skins were formed on the tool shown previously in Fig. 10. A production part taken from this tool is shown in Fig. 18. All parts were formed by inserting the blank into the die preheated to 1000°C (1350°F), locating the steel bars over the flats in the skin as shown in Fig. 10, and bringing the two halves of the die together. Weights were placed on top of the die to add pressure to the creep-form process. Following the forming process, the die was opened slightly to permit thermal contraction of the part. However, the opening was controlled to prevent rapid or non-uniform cooling at the edges. Each formed part was left in the die while the power was shut off and the die cooled slowly to approximately 530°C (500°F). The initial blanks were cut slightly oversize in both directions to allow for some skew in placing the blank in the die. After forming, the parts were cleaned, squared up, trimmed, drilled for final assembly, and etched. Trimming proved to be an unexpected source of difficulty with these parts. The first two skins to be formed were supported by an aluminum plate which had been machined to the skin geometry. This assembly was mounted on an end mill where the skins were trimmed. Both skins were cracked during this operation. Subsequently, an abrasive saw was used to trim the skins. In spite of strict precautionary measures, a third skin was lost when apparent lack of adequate support resulted in the loss of a corner. Skins formed after this point in time were trimmed to size along the long edges prior to forming; trimming of the less-critical short edges was accomplished at final assembly of the test panels.
Section 2
PHASE II ACTIVITIES

The test panels were assembled during this phase of the program. Several subassembly operations preceded final assembly. These were:

- Braze beryllium pads to clips and standoffs
- Rivet nut anchors through the brazed beryllium pads to the clips and standoffs
- Braze the stiffeners to the panel skins per Drawing J31M01045A

2.1 SUBASSEMBLY OPERATIONS

Beryllium pads were brazed to the D31M01042A standoffs, the C31M01043A-1 and -2 exterior clips, and the C31M01044A interior clips according to the drawing revisions presented in Appendix A. Pieces of BAg 18 braze alloy were cut to size and these pieces with the beryllium pads were matched drilled to the holes previously drilled in the detail parts. All parts were then thoroughly cleaned prior to assembly. The positioning of the braze strips and pads was accomplished by using the rivet holes in the parts as locators. Rene' 41 pins were inserted into these holes, and Rene' 41 spring clips were used to provide pressure to the assemblage of parts as shown previously in Fig. 13. The fixtured parts were subsequently loaded into the retort shown in Fig. 12 and subjected to the braze cycle described in Section 1.3.2. A maximum braze temperature of 1022°K (1380°F) was used in this cycle. After removal from the retort and fixturing, the parts were cleaned and X-rayed to determine braze coverage.

Machine countersinking of the rivet holes in the surfaces of the clips and standoffs which mate to the panel skins followed. Two production interior clips with brazed pads are shown in Fig. 26. All of the clips were brazed in one retort load, and all of the standoffs were brazed in a second retort load. Three clips were scrapped when they were broken during attempts to remove the Rene' 41 locating pins which had been brazed in place. Replacement clips were brazed along with a J31M01045A panel assembly in a subsequent retort load.
Fig. 26 Interior Clips Showing Brazed Beryllium Pads on Flanges
MS20427M3-4 100-degree-countersunk-head monel rivets were used to attach the nut anchors to the parts. The nut anchors (part number F5031-3P), conforming to the configuration of Drawing C31M01271, were obtained from Kaynar Manufacturing Company, Inc. These nut anchors, fabricated from A286 CRES steel, have silver-plated nuts with passivated nut baskets. Because the nut anchors were ordered prior to the decision to use riveting rather than brazing as the joining method, they were ordered with weld nibs rather than rivet holes. Consequently, it was necessary to drill the rivet holes in these parts prior to riveting. Riveting was accomplished by squeezing, rather than driving, in order to minimize shock and vibration in the beryllium parts. A small hydraulic ram with controlled travel was used to squeeze the rivets. Figure 27 shows two clips with the nut anchors installed.

One D31M01042A standoff was lost during the riveting operation. A replacement part was subsequently brazed in a vacuum furnace utilizing the braze procedures and cycle outlined previously for use with the retort. This deviation from plan was adopted because the D31M01042A standoff is too big to be included in the retort with a J31M01045A panel assembly, and use of the retort for a single part was not considered economically feasible. X-rays of the resultant braze revealed braze flow and coverage comparable to the other production standoffs, with significantly improved cleanliness of the part in the as-brazed condition.

The primary subassembly task was to braze the D31M01046A stiffeners to the D31M01041A panel skin per Drawing J31M01045A. Each test panel requires two of these subassemblies, and each subassembly consists of twelve stiffeners brazed to the panel skin. Parts for each subassembly were cleaned immediately prior to fixturing for brazing. The stiffeners and BAg 18 braze alloy strips were located on the skin with pins passed through holes in the U-stiffener fixtures, which were aligned with the holes in the parts for final assembly. When the U-stiffener fixtures had been located and clamped outside of the beryllium parts, the locating pins were removed as a precautionary measure against differential expansion between the fixtures and parts and the possibility of being brazed in place. The fixturing was assembled on one surface of the retort. A rack of steel angles was placed underneath the subassembly to provide it with greater support and to lift it off of the retort surface. This step was considered necessary due to the weight of the full-size subassembly with fixtures and
Fig. 27 Interior Clips Showing Nut Anchors Riveted in Place on Flanges; Nose Brazed Beryllium Pads
the requirement for flatness during pre-braze handling of the retort and during the actual brazing cycle. The completely fixtured subassembly, shown in Fig. 11, was anchored in the retort (see Fig. 12) with wires tack-welded to the inside walls of the retort. The retort was sealed and transferred to the box furnace where the inlet/outlet tubes and instrumentation were hooked up. The braze cycle employed for these parts was identical to that used for brazing the beryllium pads to the clips and standoffs. Upon removal from the retort and fixturing, the skin/stiffener subassembly was cleaned and X-rayed to determine braze coverage. A finished J31M01045A panel assembly is shown in Fig. 28.

X-rays of the first J31M01045A brazed panel assembly revealed good braze coverage at the ends of the stiffeners, but undesirable void areas towards the center of the stiffeners. It is unknown whether the voids were the result of lack of flow of the braze alloy, or whether they were caused by relaxation of the brazing fixtures after the mating surfaces had been wetted by the braze alloy. Voids of the latter type had been observed previously in one of the trial brazes as discussed in Section 1.3.2 of this report.

It was subsequently determined that the D31M01041A panel skins being formed on the tool shown in Fig. 10 did not have the same flatness tolerance as the skins formed initially on the tool shown in Fig. 15. Skins from the latter tool had been used in the brazing trials described previously. To compensate for the greater deviation from flatness in the production panel skins, the 17-7 PH steel U-stiffeners used to fixture the parts for brazing were replaced with Hastelloy X U-stiffeners, and the thickness of braze alloy was increased from 0.0076 cm (3 mils) to 0.0152 cm (6 mils). The Hastelloy X stiffeners were specified because of the higher strength of this alloy at brazing temperature in combination with a good match in thermal expansion properties with beryllium throughout the brazing cycle. Thus, the Hastelloy X stiffeners were expected to promote better contact between mating parts during brazing.

The second J31M01045A panel assembly was brazed after the above changes had been incorporated into the braze procedure, and X-rays revealed braze coverage of better than 90 percent. However, the retort was jostled during transfer from the assembly
Fig. 28 Production Stiffener-Skin Assembly After Brazing
area to the furnace, and as a result, one end stiffener slipped in the fixturing and a replacement clip, which had been inserted in this retort load to braze pads to the flanges, became wedged under the edge of the panel skin and initiated a crack in the skin. As a result, this brazed assembly was subsequently scrapped.

In order to minimize the movement of the loaded retort, the third J31M01045A panel assembly was brazed in another furnace adjacent to the assembly area. Bottled argon was used for this braze cycle in place of the liquid argon system available with the furnace used previously. In order to compensate for the higher level of impurities in the bottled argon as opposed to the liquid argon, titanium shavings were placed inside the retort. X-rays of this brazed assembly revealed about the same braze coverage as on the previous assembly. However, substantial flow of the braze alloy out of the joint was experienced, as shown in Fig. 29. This apparently was caused by the presence of the titanium shavings since similar flow out of the joint was not experienced in either prior or subsequent assemblies utilizing the same braze cycle and procedures. This assembly also experienced a slight movement of the center stiffener relative to the skin which was later found to be within acceptable tolerances. This led to the decision to leave the locating pins in place in those U-stiffeners which are secured to the walls of the retort. The fourth and fifth J31M01045A panel assemblies showed no adverse effects as a result of this decision and revealed perfect alignment between stiffeners and panel skin. The fourth J31M01045A panel assembly is the assembly shown in Fig. 28. Both this assembly and the third panel assembly in Fig. 29 are shown in the as-brazed condition. Note the differences in surface discoloration, which is apparently due to the presence of titanium shavings in the retort with the third panel assembly.

In general, the D31M01041A panel skins contained some warp in the as-formed condition which was effectively removed during the brazing process. When the third J31M01045A panel assembly was removed from the retort, it was generally flat but a local lifting of the skin-stiffener composite at one end of one of the central stiffeners was observed. It was decided upon fitting up the parts for final panel assembly that while the panel could be drawn down to the standoff in this area, there was significant risk of loss of parts due to induced stresses. Consequently, this area of the panel assembly was straightened by refixturing the panel for brazing, sealing it in the retort,
and repeating the braze cycle to a maximum temperature of 1011°K (1360°F). This procedure effectively flattened the panel assembly in the area of interest. X-rays of the panel taken subsequently showed no degradation of the braze as compared to X-rays of the panel following the initial braze cycle.

2.2 FINAL PANEL ASSEMBLY

NAS1579-V3H5 titanium (6Al-4V), flat pan head, full thread screws with torq-set recess were used to assemble the clips and standoffs to the brazed skin/stiffener sub-assemblies. To prevent damage to the beryllium panel skins due to possible interference between the drilled holes and the screw head-to-shank radius, washers were placed under the screw heads. The hole diameter in the panel skins, as called out on Panel Assembly Drawing J31M01040, is 0.483-0.493 cm (0.190-0.194 in.); the screw shank diameter is 0.483 cm (0.190 in.) maximum, and the screw head-to-shank radius is 0.025-0.051 cm (0.010-0.020 in.). Thus, a possible maximum interference of 0.010 cm (0.004 in.) exists if the washer is not used.

Note that although Assembly Drawing J31M01040 includes reference to insulation and the super-alloy test substructure, these items are not a part of this program. However, full-size holes have been provided in the clips and standoffs for subsequent attachment to the substructure.

One of the fully assembled beryllium test panels is shown attached to an aluminum base plate in Fig. 30 prior to shipping.
Section 3
QUALITY ASSURANCE

To ensure that the resulting hardware was in compliance with the engineering requirements set forth in the drawings, quality controls were exercised at a number of points during the manufacture of the beryllium test panels. One longitudinal and one transverse tensile coupon were removed from each sheet of the initial beryllium material order for verification of the mechanical properties required by specification. The results are presented in Section 1.1 of this report. The tools fabricated for this program, and the detail parts subsequently formed on these tools, were subjected to dimensional inspection. Etching was employed to identify cracks after all forming, milling, and drilling operations. In general, cracked parts were easily identified by the audible fracture of the part when cracking occurred.

Radiographic inspection (X-rays) was performed on all brazed joints. These films were furnished to the project leader with comments relative to the acceptability of the braze. Acceptance or rejection of the brazed parts was the prerogative of the project leader. The films showed some void areas in all brazes, as might be expected. Braze coverage in all instances was between 85 and 97 percent with the exception of the first J31M01045A panel assembly, where braze coverage was between 65 and 70 percent. No large void areas or concentrations of voids were found. Time-temperature records of all braze cycles were also maintained.

The assembled panels were dimensionally inspected prior to shipment. As a result of this inspection, both panels were accepted as being fully qualified to perform as desired by engineering requirements.
Section 4
RECOMMENDED PRECAUTIONS WITH BERYLLIUM PANELS

When used in structural applications, beryllium thin-gage sheet material has characteristics which set it apart from common sheet materials. Because of its very high modulus of elasticity, it is exceedingly stiff; very small elastic deformations result in unusually high stresses in the material and may cause fracture. Care must be taken to ensure that edges are protected against accidental out-of-plane loads. For this reason, when parts are transferred from one area to another, they should first be placed in a protective container.

Structural materials such as aluminum are quite forgiving to the loads encountered during assembly, and installation. These loads, therefore, are not often considered in the design of the hardware. In contrast, beryllium is not forgiving, and care should be exercised to avoid forcing the material to absorb dimensional mismatches. Such loads often exceed the loads for which the part was designed. Shims must be employed to prevent damage to the part. If holes are drilled in the part, special burr-type drills should be used in conjunction with light pressures, firm backup, and etching after drilling.

Beryllium has a strong affinity for oxygen, which forms a protective oxide coating over the metal. This coating effectively stops further oxidation. In the as-cleaned or etched condition, the material has a silvery appearance and the surface possesses relatively low emissivity properties. The formation of beryllium oxide on the surface dulls this finish and increases emissivity at the same time. The surface may be further dulled by the application of heat. However, this may cause warping and/or fracture if thermal gradients are present in the panel.

Beryllium has poor resistance to corrosion in that water containing normal impurities will cause localized corrosion. Therefore, parts should be stored in a dry area. Beryllium is also subject to electrolysis when used in a number of dissimilar metal
combinations. It reacts with steels, stainless steels, nickel alloys, and some aluminum alloys such as 7075 and 6061. It does not react with titanium. In the beryllium panels fabricated for this program, A-286 CRES steel nut anchors have been attached to the beryllium parts, and stainless steel washers have been placed underneath the screw heads. These mating surfaces should be kept dry and should be inspected periodically if the panels are placed in storage.
Section 5
CONCLUSIONS

Two beryllium test panels were successfully formed, assembled, and delivered to the George C. Marshall Space Flight Center. This program objective was accomplished after a number of forming/processing problems were satisfactorily solved. Having solved these problems, additional panels can now be fabricated with considerably less material risk and labor. LMSC has had similar experience with other production programs for beryllium structures where initially high rejection rates are now at about two percent.

Some complex stiffener sections were formed for this program without great difficulty. Significantly, however, these parts were relatively small, and larger parts, for example the panel skins, proved to be much more difficult to form because of their size and the necessity for uniform heating and cooling. This problem could be overcome by forming the skins in roughly square sections and splicing them by brazing. Alternately, it might be desirable to provide longitudinal slip joints at these intersections.

Experience gained in the fabrication of the D31M01042A standoff indicates that future standoff designs should be simplified by dividing the part into two or more segments. This part requires 48 metal forming operations and 62 drilled holes (with riveted nut anchors). The probability of loss due to cracking in this part, consequently, is very high, and can be accompanied by a rather significant loss in labor investment.

Brazing of A286 CRES steel nut plates to beryllium was found to be impractical both from a manufacturing and design point of view. However, good beryllium-to-beryllium brazements were obtained with careful control of the braze cycle. Brazing within a retort, although satisfactory for brazing the two beryllium test panels, is not recommended for large production runs because of the time required to seal and handle the retort.
The beryllium sheet material used in this program exhibited a minimum elongation in 2.45 cm (1.0 in.) of 11.5 percent and a maximum elongation of 27.0 percent; however, the material did not appear to be any easier to form than sheet material with significantly lower percent elongation. It was concluded that the room temperature tensile coupon pull is not indicative of formability. A more appropriate test might be a wide-sheet bend test performed at forming temperature. Success in this test depends upon the ability of the material to strain in directions normal to the direction of primary strain which, in turn, depends upon Poisson's ratio. Beryllium exhibits a very low elastic Poisson's ratio in the plane of the sheet, on the order of 0.10. Tests indicate that the value in the thickness direction of the sheet is much smaller. Thus, improved uniaxial elongation in beryllium, while desirable in the material in service, may not be expected to offer significant relief in forming the material.

The beryllium sheet material for this program exhibited a somewhat larger coefficient of thermal expansion at forming temperature than that reported in the literature*. The latter value was reported to be approximately $9.0 \times 10^{-6}$ cm/cm ($9.0 \times 10^{-6}$ in./in.) at $1033^\circ$K (1400°F), whereas the apparent value observed during this program was approximately $10.0 \times 10^{-6}$ cm/cm ($10.0 \times 10^{-6}$ in./in.) at the same temperature. Further substantiation of this variance is required because of the necessity for matching the coefficient of thermal expansion of beryllium sheet to that of the tool material at forming temperature in order to obtain large parts that are satisfactory.

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Appendix A

DRAWING REVISIONS TO REPLACE BRAZED NUT ANCHORS WITH RIVETED NUT ANCHORS
CHANGES TO DRAWING J31M01040A

• Sheet 1 of 2
  • Omit (30) BAg 18 Braze Alloy callout in Section H-H
  • Add Note 4: Attach 31M01271-1 nut anchors with MS 20427M3-4 100 degree countersunk head, monel rivets, after brazing (with BAg 18 braze alloy) a 0.4 in. by 1.0 in. pad from 0.030 beryllium stock to the 31M01042A-1, 31M01043A-1, 31M01043A-2 and 31M01044A-1 parts between the nut anchor and the parts. Material for the beryllium pads shall be per MIL-B-8964 (except the elongation required by par. 3.3 shall be 10 percent in 1 in.).

• Sheet 2 of 2
  • Omit (30) BAg 18 Braze callout in Section P-P
  • Add locating sketch for beryllium pads on 31M01042A parts:
- Add locating sketch for beryllium pads on 31M01043A parts:

![Sketch of beryllium pads on 31M01043A parts]

NOTE: (4) 31M01043A-2 OPPOSITE
- Add locating sketch for beryllium pads on 31M01044A parts:

![Sketch of beryllium pads](image)

MSFC—RSA, Ala
Details of the fabrication and assembly of two 99 cm by 99 cm (39 in. by 39 in.) beryllium heat shield test panels for delivery to the George C. Marshall Space Flight Center are presented. Each panel consists of two hat-stiffened, formed skins which overlap a transverse slip joint at the center of the panel; clips join the two skins at the slip joint, and continuous standoffs are provided at the ends of the panel. The hat-stiffeners are joined to the skin by furnace-brazing, using the braze alloy BAg18. The parts are generally 0.051 cm (0.020 in.) thick. Tools used to form the detail parts are shown, together with the results of preliminary forming and brazing trials to verify processing techniques. Problems subsequently encountered in the manufacture of the panels are discussed.